Experimental Investigation on the Flexural Capacity of Reinforced Concrete Beams with Treated Wastewater and Recycled Concrete Aggregates

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Abstract

Eco-friendly concrete is the most recommended sustainable option to reduce the excessive diminution of concrete natural resources and the high generation of greenhouse gas emissions. Therefore, the present study explores the feasibility of employing treated wastewater (TWW), recycled concrete aggregates (RCA), and fly ash (FA) in concrete mixes. A total of 4 reinforced concrete (RC) beams were investigated under 4-point bending setup with three parameters investigated; namely, mixing water (fresh water and TWW), coarse aggregates (gabbro and RCA), and cementitious binders (cement and FA). The experimental results revealed that the beams' ductility was decreased by 9% and 16% with TWW and RCA, respectively. Moreover, the flexural performance of the TWW-RC beams was decreased by 14%, whereas RCA-RC beams showed comparable flexural strength to its counterpart with natural aggregates. In addition, the utilization of FA at a 20% replacement ratio enhanced the flexural strength by 5% to 7%.

Keywords: Treated wastewater; Eco-friendly; Recycled concrete aggregates; Flexural capacity; Ductility

1 Introduction

Concrete is the workhorse material in the construction industry in the 21st century. Nonetheless, the worldwide production of concrete has significantly increased over recent years due to population boom and urbanization (Abushanab & Alnahhal, 2021). The global concrete manufacturing rate has currently reached 10 billion tons per year, with an expectation to explosively increase by 80% by 2050 (Abushanab et al., 2021). The growing volume of concrete is raising concern about carbon emissions and overwhelming employment of concrete natural ingredients. Previous studies have reported that the utilization of fresh water (FW), natural aggregates, and ordinary Portland cement (OPC) for concrete applications is 2, 48.3, and 4.1 billion tons per year, respectively (Abushanab et al., 2021; Abushanab & Alnahhal, 2022b). Moreover, 10% of the worldwide CO_2 emissions are due to the concrete industry (Abushanab & Alnahhal, 2022b). In response, recyclable concrete ingredients should be adopted for concrete elements.

In a bid to save the environment and concrete natural resources, researchers have recently proposed the employment of treated wastewater (TWW), recycled concrete aggregates (RCA), and fly ash (FA) in reinforced concrete (RC) structures (Abushanab et al., 2021; Abushanab & Alnahhal, 2022b; Abushanab & Alnahhal, 2022c). Several studies have investigated the impact of utilizing TWW on plain concrete properties (Meena & Luhar, 2019; Abushanab et al., 2021; Arooj et al., 2021; Abushanab & Alnahhal, 2022a). Abushanab & Alnahhal (2021) reported that the mechanical properties of TWW concrete decreased by 5% to 12% compared to that made with FW. Furthermore, the authors demonstrated that the chloride permeability was decreased by 40% at a TWW replacement ratio of 100%. Asadollahfardi et al. (2016) obtained similar results. Moreover, the employment of RCA in concrete applications has been reviewed by several researchers (Behera et al., 2014; Abushanab et al., 2021; Abushanab & Alnahhal, 2022b). It has been shown that concrete with 100% RCA experienced a 30% drop in compressive strength and a 13% increase in chloride permeability (Behera et al., 2014; Abushanab & Alnahhal, 2022b). Due to the inferior properties of TWW and RCA concrete, researchers have recently incorporated FA in concrete to improve the characteristics of RCA concrete (Abushanab & Alnahhal, 2021; Abushanab & Alnahhal, 2022b). Abushanab & Alnahhal (2022b) reported that partially replacing OPC with FA in TWW and RCA concrete has improved concrete chloride permeability by 50%. Furthermore, the influence of RCA and FA has been demonstrated for RC applications (Choi & Yun, 2013; Seara-Paz et al., 2018). Choi and Yun (2013) showed that RC beams with RCA had a 20% drop in the flexural strength. In addition, Seara-Paz et al. (2018) recorded narrower flexural cracks in RCA-RC beams compared to those made with natural aggregates.

Even though the characteristics of plain concrete with TWW, RCA, and FA have been tested, a gap remains in their combined effect on the flexural capacity of RC beams. Accordingly, this study investigated the impact of TWW, RCA, and FA on the flexural performance of RC beams.

2 Experimental Program

2.1 Mixing Water

The study at hand investigates two types of mixing water: FW and TWW. The TWW used was obtained from a local wastewater treatment plant. The chemical composition and concentration of FW and TWW are listed in Table 1.

Table 1: Chemical Properties of FW and TWW

Component	FW (mg/l)	TWW (mg/l)
Sulfate (SO_4^{-2})	6	6
Zinc (Zn^{+2})	0.0046	0.11
Phosphate (PO_4)	<0.03	9.19
Chloride (Cl^-)	14.1	511
Total dissolved solids	93	1690
Total suspended solids	2	3

2.2 Aggregates

In this study, coarse natural gabbro aggregates and RCA were considered. The particle size distribution of both types of aggregates was between 4.75 and 20 mm, as shown in Fig. 1. Furthermore, washed sand with a particle size of 0.075 to 4.75 mm was employed in the mixes as fine aggregates. The properties of fine aggregates, GA, and RCA are presented in Table 2.

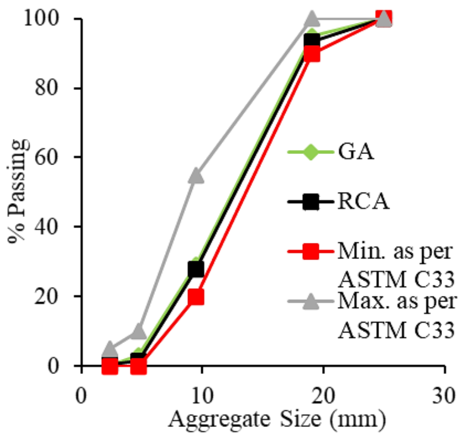

Fig. 1: Particle Size Distribution of GA and RCA

Table 2: Properties of Sand, GA, and RCA

Property	**Sand**	**GA**	**RCA**
Los Angeles Abrasion (%)	—	8.9	17.6
Water Absorption (%)	0.6	0.72	3.51
Specific Gravity	2.63	2.91	2.55

2.3 Cementitious Binders

Two types of cementitious binders were considered in this study: OPC and FA. The OPC considered had a particle size distribution of 10 to 90 µm and specific gravity of 3.15. The FA used was of type F with a particle size distribution and specific gravity of 3 to 55 µm and 2.15, respectively.

2.4 Steel Reinforcement

Deformed steel bars with diameters of 8, 10, and 12 mm were used to reinforce the RC beams. The characteristics of the bars are shown in Table 3.

Table 3: Characteristics of Steel Reinforcement

Property	**Bar Diameter (mm)**		
	8	**10**	**12**
Yield Strain	0.0268	0.00267	0.00266
Yield Strength (MPa)	512	515	525

2.5 Concrete Mixtures

In this study, a total of four concrete mixtures were fabricated. The parameters considered were the type of concrete mixing water (FW and TWW), coarse aggregates (GA and RCA), and cementitious binders (OPC and FA). Both TWW and RCA were employed at a 100% replacement ratio, whereas FA was tested at replacement ratios of 0% and 20%. The volume replacement method was used for RCA, whereas the weight replacement method was considered for both TWW and FA. Concrete mix ingredients are presented in Table 4. Regarding the notation used for the concrete mixes, the first digit belongs to the mixing water type (F for FW and T for TWW). The second digit corresponds to the coarse aggregate type (G for GA and R for RCA). The third digit belongs to the cementitious binders (C for 100% cement and F for a mixture of 20% FA and 80% cement).

Table 4: Concrete Mix Ingredients

Mix	Mix Proportion (kg/m^3)						
	FW	TWW	OPC	FA	GA	RCA	Sand
F-G-C	156	0	349	0	1075	0	708
T-G-C	0	156	349	0	1075	0	708
T-R-C	0	156	349	0	0	942	708
T-R-F	0	156	279	69	0	942	708

2.6 Concrete Compressive Strength Test

The compressive strength of concrete was tested at 28 days using 3 cylinders of 100×200 mm for each mix as per ASTM C39/C39M-20 (ASTM C39/C39M-20, 2020).

2.7 Concrete Flexural Tensile Strength Test

The flexural tensile strength of concrete was tested at 28 days using 3 prisms of 100×100×500 mm for each mix as per ASTM C78/C78M-18 (ASTM C78/C78M-18, 2018).

2.8 Flexural Capacity Test of RC Beams

Four RC beams measuring 180 mm width, 250 mm height, and 2000 mm length were constructed and tested up to failure under a four-point flexural bending setup to evaluate the effect of concrete mixes on the flexural capacity of RC beams. The beam's designations followed the same designations of the concrete mixes. To measure the beams' displacement, two linear variable displacement transducers (LVDT) were added at each midspan. The tests were performed using a displacement rate of 1 mm/min. The details of the test setup and instrumentations are shown in Fig. 2.

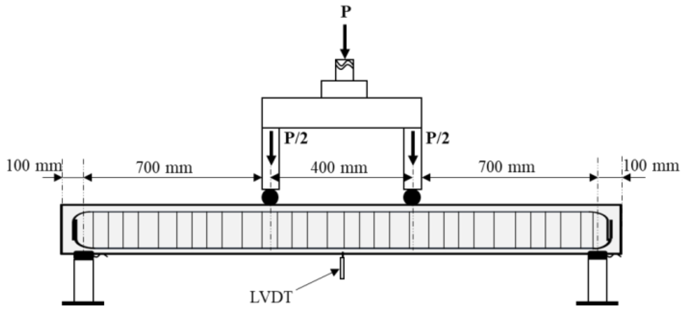

Fig. 2: Details of Test Setup and Instrumentations

3 Results and Discussion

3.1 Concrete Compressive Strength

Table 5 lists the compressive strength results. It can be revealed that mix T-G-C had a 6% lower compressive strength than mix F-G-C, attributable to the high amounts of phosphate and zinc in TWW, which alerted the hydration of OPC. In addition, the results show that mix T-R-C recorded 10% lower compressive strength than mix T-G-C due to the residual mortar on RCA, which affected the interface between aggregates and matrix and consequently generated more internal cracks. Moreover, mix T-R-F, which incorporated 20% FA, reported a drop of 16% in the compressive strength compared to T-R-C. This could be attributed to the decreased OPC hydration products due to the reduced OPC content, which consequently reduced the binding between aggregates and matrix. These observations agree with Sunayana & Barai (2019) and Alnahhal et al. (2023).

Table 5: Concrete Mechanical Properties

Specimen ID	Compressive Strength (MPa)	Flexural Tensile Strength (MPa)
F-G-C	57.03	3.77
T-G-C	53.50	3.29
T-R-C	48.04	3.43
T-R-F	40.54	2.96

3.2 Concrete Flexural Tensile Strength

The flexural tensile strength results are depicted in Table 5. It could be noticed that the use of TWW in mix T-G-C decreased the flexural strength by 13% compared to mix F-G-O, ascribable to the high pollutants of TWW. Furthermore, mix T-R-C achieved comparable flexural strength to mix T-G-C, indicating that RCA had no effect on the flexural strength of concrete. On the other hand, mix T-R-F reported 14% lower flexural strength than mix T-R-C due to the decreased OPC products. Abushanab & Alnahhal (2022b) also reported similar observations.

3.3 Flexural Strength of the Beams

Fig. 3 illustrates the load-deflection curves of the beams. In addition, Table 6 presents a summary of the ultimate load capacity and ductility index of the beams. It can be seen from the results that beam T-G-C had a drop of 14% and 9% in the ultimate flexural capacity and ductility index, respectively, compared to beam F-G-C. Furthermore, the deflection of beam T-G-C at service was 17% higher than that of beam F-G-C. The drop in the flexural properties of beam T-G-C is attributed to the chemical contaminants of TWW, which decreased the OPC hydration products and thus decreased the binding capacity between reinforcement and surrounding concrete. It can also be seen that beam T-R-C showed comparable flexural strength to its counterpart with natural aggregates. However, the beam recorded 9%, 6%, and 16% lower failure load, deflection, and ductility than beam T-G-C, respectively, compared to beams with natural aggregates. This might be attributed to the cracks and voids developed at the interface between aggregates and concrete matrix, which increased the brittleness of the beams. On the other hand, the flexural strength of beam T-R-F was increased by 7% and 5% compared beams TG-0 and TR-0, respectively. In addition, beam T-R-F reported marginally higher ductility than beam T-R-C. The improvement achieved with the 20% FA is ascribed to the calcium-silicate hydrates (C-S-H) gel, which densified the matrix and enhanced the bond strength between concrete and reinforcement. The obtained results are in line with Yoo et al. (2015).

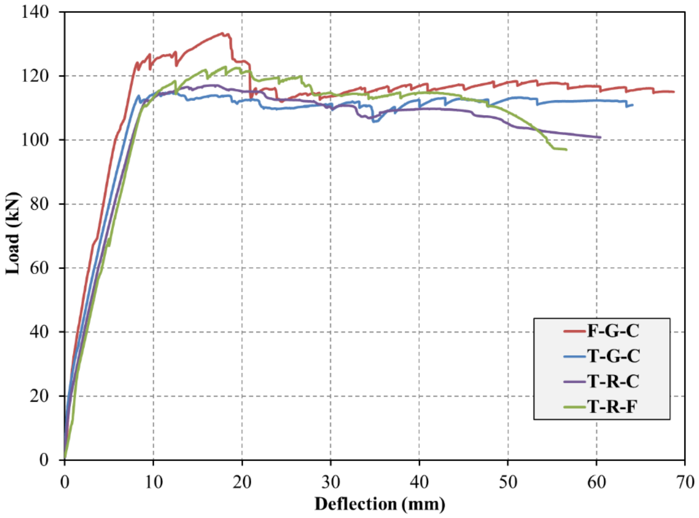

Fig. 3: Load-deflection curves of the beams

Table 6: Beam test results

Beam ID	Ultimate Strength (kN)	Ductility Index
F-G-C	133.35	8.32
T-G-C	115.12	7.60
T-R-C	117.09	6.39
T-R-F	122.90	6.43

4 Conclusion

In this study, the effect of TWW, RCA, and FA was investigated on the mechanical properties of concrete and flexural strength of RC beams. A total of four concrete mixtures were manufactured. The parameters considered were the type of concrete mixing water (FW and TWW), coarse aggregates (GA and RCA), and cementitious binders (OPC and FA). Based on the obtained results, the following conclusions are drawn:

1. TWW has a slight effect on the compressive strength of concrete. Nonetheless, RCA and FA showed a reduction of 10% and 16% in the compressive strength, respectively.
2. The use of TWW decreased the flexural strength and ductility of the beams by 14% and 9%, respectively.
3. RCA-RC beams had 9% and 16% lower failure load and ductility compared to beams with natural aggregates.
4. Incorporating FA with RC beams improved the flexural strength by 5% to 7%.

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